Optical and IR Interferometry from Ground and Space
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The Practice of Astrometry in Space with the Space Interferometry Mission Instrument

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Abstract. A short tutorial covering the basics of astrometry and interferometry relating to the SIM mission is presented. The material includes: a description of interferometry, the definition of delay, how it is measured, how it is converted into an angle, some of the difficulties of space interferometry, global and inertial coordinate frames, the SIM Grid and error sources associated with the mission.

Introduction

Astrometry is the precise measure of relative positions, distances, and motions of the celestial bodies. In the case of SIM the basic measure taken is the angle between the bodies. In most cases the bodies are stars for which the angle between them is to be measured to a few micro-arcseconds. In order to make measurements of this precision, optical interferometry is used. The change in angle with time along with some indication of the distance the object is from the observer will give velocity perpendicular to the line of sight to the object/s.

Optical Interferometry is the measurement of distance based on the interference of two or more rays of light. The wave nature of light is such that light from the same source can be combined with itself to interfere, much the same as ocean waves interfere with each other. The result of the interference of two waves or beams is a change in the intensity of the combined beams. Here we will examine the case of two beams of exactly the same intensity. Precise control of the length of the path of one ray or beam compared to the other will vary the intensity from the nulled condition of zero intensity (destructive interference) to a maximum intensity (constructive interference) that is twice the intensity of each beam. Also, if the path that each beam travels from the source to the point of interference in some way distorts the beam (wave front), the maximum and minimum values of intensity will no longer be zero and twice that of an individual beam but some intermediate value. This represents a change in the visibility of the maximum and minimum intensity.

Figure 1 illustrates the above description. In the figure, the source of each beam is a star that is being observed. Since the starlight of interest is very weak, the light is collected with telescopes, compressed to a smaller beam size (in order to make the instrument smaller and more cost effective) and then interfered. The diagram in the upper right illustrates the change in the intensity of the interfered beams as a function of small changes in the path length of one beam versus the other. Zero at the center of the "delay" axis corresponds to exactly the same path length traveled by each beam. In this particular case the rapid decrease in intensity maximum and minimum to a mean value is the signature of the interference of light composed of a broad range of wavelengths. The signature from a very narrow range of wavelengths of light on the other hand is a very slow decrease in the maximum and minimum intensity as a function of change in the path length of one beam with respect to the other. The interference of white light (light with a broad range of wavelengths) produces what is called a white light fringe. This fringe only occurs near zero delay as illustrated.

The white light fringe is key to obtaining the astrometric observable the delay. For an astrometric interferometer, the delay can be written mathematically as the dot product of a unit vector to the star and the baseline vector (a description of the length and direction in space between the telescopes).

$$d = B\cos(\theta), \qquad (1)$$

where: d is delay, B is the baseline vector and θ is the angle between unit vector to the star and the baseline vector

1. Measuring the Delay

In order to measure the delay with respect to the white light fringe position of a star, an artificial delay is generated in the interferometer with a delay line. The amount of delay the delay line adds or subtracts from the beams is measured with extremely high accuracy in order to make a state-of-the-art astrometric measurement. In the case of SIM this is done with an internal laser interferometer gauge that uses a laser beam to retrace and measure exactly the same path the starlight travels within the interferometer instrument. The path measured is from each telescope to the combiner where the starlight is combined and interfered. This device enables a distance measurement that is precise to a small fraction of the wavelength of the laser light (nearly one-millionth the length of a wave of light or 10^{-12} meters). Equation 1 above describing the delay can now be written as:

$$d = (\vec{B} \cdot \vec{s}) + C, \qquad (2)$$

where: $\vec{s}$ is the unit vector to the star and C is the zero point of the metrology gauge.

A measurement of similar precision must also be made of the white light fringe position generated from the starlight. The ability to measure the position of the white light fringe is of prime importance as it acts as a fiducial from which to measure relative delays. In fact the delay measured between two white light fringes is used as the basic data that is converted into an angle on the sky that exits between the two stars that have been observed. Hence the precise position of the white light fringe is all important. A significant amount of technical effort is being focused on the development of this fringe detector.

2. Ground vs. Space Astrometry

Most instruments used on the ground are fixed to the earth and rotate with it. The earth forms a very stable base and rotates at a predictable rate. Here the baseline orientation can be measured to ~100 micro-arcseconds (VLBI) and ~1 milli-arcseconds (optical). The major error source in these measurements is due to turbulent atmospheric mixing of warm and cold air randomly changing the path length through the atmosphere.

For an interferometer in space however, the baseline stability is many orders of magnitude less. A spacecraft has little mass and generally an asymmetric shape making it's attitude susceptible to small forces such as gravity gradients, solar radiation pressure, and reaction forces to motions of components of the spacecraft itself. To deal with these effects, the baseline orientation has to be measured and controlled with the help of star trackers and "guide interferometers" that provide attitude information to arcsecond and a few micro-arcsecond accuracy respectively. To do this the guide interferometers end up being made to the same specifications as the "starlight interferometer."

3. SIM Classic External Metrology

The measurement of angles of a few micro-arcseconds corresponds to accurately measuring distances to *sim*0.1 nano-meters or 100 pico-meters. The rigidity of the material that makes up the spacecraft and instrument cannot be relied on to hold tolerances this small. Instead optical trusses are used to measure critical distances and control the distances or measure them in order to calculate and subtract errors caused by changes in position. For the SIM Classic design external metrology is used to provide the relative orientation and lengths of the baselines of the two guide interferometers compared to the science interferometer. This is implemented with an external metrology reference structure, metrology gauges and optical fiducials. For SIM classic all three baselines are nominally parallel.

4. The Virtual Stable Baseline

Even with the best control, the SIM spacecraft's attitude will not be stable to the micro-arcsecond level. To obtain a baseline stable in space that the science interferometer measurement can be tied to (a virtual baseline), the attitude of the spacecraft is measured by the guide interferometers and corrected for relative position errors as measured by the external metrology. All of the baselines (guides and science) are moving, only the virtual baseline is stable in space.

5. SIM Astrometric Measurements

While the combination of the guide interferometers and external metrology maintains a stable virtual baseline, the science interferometer moves between a number of stars within the field of regard (~15 deg.). The science interferometer measures the position (angle) of a star in the direction of the (virtual) baseline. To obtain a two dimensional position of the star on the sky, the SIM instrument must revisit this tile ($\sim$ 15 deg area of sky) and measure the angles of the same stars but this time with the baseline orientation rotated $\sim$90 deg. on the sky compared to the first visit.

By stepping from one tile to the next, the complete sky will be covered. In order to tie these measurements together, grid stars are chosen, measured and referenced to extra galactic objects. Position, parallax and proper motion are measured for all grid stars. The science targets are in turn measured with respect to these grid stars. There are 8 to 12 grid stars per tile. The tiles overlap and cover the complete sky (4π steradians).

6. The Astrometric Grid

The astrometric grid is composed of $\sim$3,000 stars and $\sim$50 bright QSOs spread uniformly over the whole sky. The stars are measured in a grid campaign that consists of a predetermined series of tile observations that cover 4 π. The current plan is to conduct 4.5 grid campaigns over the five year mission. Simulations of grid observations show that grid star positions with $\sim$8 micro-arcsecond single measurement accuracy result in a five year mission accuracy of: $\sim$4 micro-arcsecond in position, $\sim$2 micro-arcsecond in proper motion, and $\sim$4 micro-arcsecond in parallax.

7. Selection of Grid Stars

Ideally the $\sim$3,000 grid stars are all bright (<13 mag) extra-galactic objects with zero proper motion and zero parallax at the 4 micro-arcsecond level. Unfortunately there aren't any of these objects, the vast majority of grid stars have to be within our galaxy. So, what type of stars do we want in the grid? They need to be bright (<13 Mag), single stars (stars with no companions as viewed on the sky). Since the stars are in the galaxy, we need to solve for position, proper motion, and parallax as alluded to above. Also, since the stars are in the galaxy their motion will be detected and must then be accounted for in the data reduction. To help do this, $\sim$ 50 QSOs are also measured and used as non-moving reference points in the grid, pinning it to an inertial coordinate frame.

What types of stars make good grid objects? This has not been totally resolved. The selection of grid stars for SIM including analytical and observational research is the main topic of a SIM NRA (`http://spacescience.nasa.gov/nra/99-oss-04/`). Current thinking leans toward K giant stars at a distance of 1-2 kiloparsecs as leading candidates for the majority of grid stars. The main advantage of K giant stars at a distance of 1 to 2 kiloparsecs is that unseen stellar and planetary companions will not produce a wobble greater than 4 micro-arcseconds over the 5 year mission. Long period companions (>30 yr. periods) tend to produce linear motion of the K giant on a 5 year time scale. Short period companions on the other hand (Jupiter mass 1 yr. period) have a wobble amplitude < 4 micro-arcsecond.

8. SIM Error Sources

The SIM astrometric error budget is being presented in a separate paper by Mike Margulis. This budget includes instrument measurement errors that are independent of the target. Specific items covered are: Thermal distortion errors, Pointing and pathlength effects, Diffraction effects, Geometrical optics effects, Optical surface property effects, Beam walk effects, Stellar aberration, Baseline co-parallelism, and Systematic fringe measurement errors. Errors dependent on target signal-to-noise covered are: Photon counting noise effects, Detector noise, and Visibility degradation effects. Figures 2 and 3 show the error tree and mathematical model respectively.

9. Types of Astrmetric Measurements

There are three basic types of astrometric measurements envisioned. They are:

1 Science measurements that are concurrent with grid measurements. These can consist of ~45 visits during the 5 year mission. The accuracy of the measurements is the same as the "grid" for a 5 parameter solution (ra, dec, pra, pdec, and pi).

2 Science measurements separate from the grid campaign. For a desired accuracy somewhat worse then the "grid" (4 micro-arcsecond parallax) there will be fewer visits to the object then grid objects. The measurements will have a minimum of 4 grid stars observed to calibrate the baseline (normally 6). For a desired accuracy at or greater than 4 micro-arcseconds this becomes very expensive in observing time. Many more than the minimum number of grid stars will have to be observed as astrometric calibrators in order to average out random errors in the grid star measurements.

3 Narrow angle measurements. These measurements use nearby reference objects whose positions and parallaxes are unknown.

10. Astrophysical Error Sources

At least two types of error terms will be removed by the project at the Interferometry Science Center. These can be understood in terms of relativistic corrections. The first is proportional to the spacecraft velocity divided by the speed of light (v/c). This will include terms due to the motion of the spacecraft around the solar system barycenter and a rough correction for the sun's motion around the galactic center. The second term is due to the gravitational lensing effects by solar system objects, the Sun and the 9 planets, the larger moons of the planets and the larger asteroids. For instance in the case of the limb of Jupiter this effect is ~ 17 milli-arcseconds. One must therefor know the impact parameter with respect to Jupiter to ~4 milli-arcsecond.

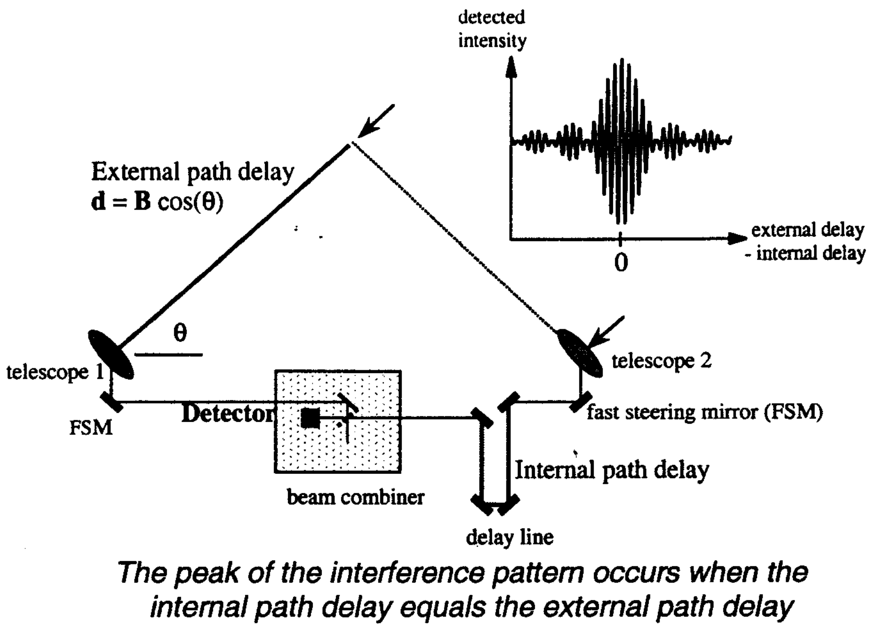

Figure 1. A typical scheme of an interferometer.

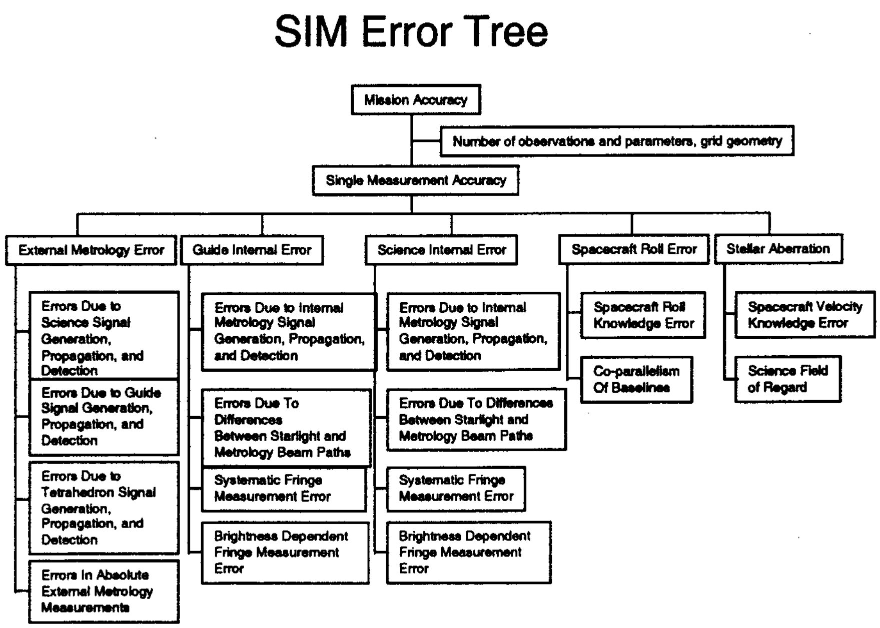

Figure 2. SIM astrometric error structure.

SIM Error Model

1 Simplified the astrometric error can be decomposed for observational planning purposes as:

1 (Current Classic error budget model)

1 $err^2 = c_1*(angle)^2 + c_2*(time)^2 + \sigma_i^2 + (c_3/Nphot)$
   - $c_1 \sim$ 18 μas^2 (angle ~ field of regard/15 deg.)
   - $c_2 \sim 7$ μas^2 (time ~ interval for measurement/hr)
   - $\sigma_i \sim 1.3$ μas (time and angle independent term)
   - $c_3 \sim$ $3.6x10^7$ μas^2 (N= # detected photons)

1 Example: single measurement accuracy
   - 11 mag star
   - 30 sec integration
   - 15 deg FoV
   - 1 hr thermal drift time
   - 8.4 μas

Figure 3. SIM astrmetric error model.